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VERY-HIGH-BURNUP VAPOR-TRANSPORT FUEL-PIN CONCEPT FOR LONG-LIFE NUCLEAR REACTORS

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ABSTRACT

A very-high-burnup, vapor-transport fuel-pin concept is presented. Sample calculations using the design charts given in the report show that fission densities in the range of 10^{20} to 10^{21} fissions per cubic centimeter are conservatively predicted. The fuel within the pin can be operated at sufficiently high inside surface temperatures so that fuel redistribution will occur by design. This feature accommodates and relieves the adverse effects of nonuniform power distribution, hot spots, and nonuniform burnup. Changes in reactor reactivity due to high burnup are minimized with the vapor-transport fuel-pin concept.

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SUMMARY

A very-high-burnup, vapor-transport fuel-pin concept for long-life, high-power reactors is presented. The fuel pin is essentially a pressure tube with a relatively thin lining of fuel on the inside surface of the tube. The inside fuel surface is designed to operate at temperatures high enough to permit fuel redistribution by vapor transport. A relatively large central void volume is provided to allow room for the gaseous fission products that are released. Design curves are derived which permit the conservative design of these fuel pins for any desired fuel or tube materials.

Sample calculations show that atom burnups far in excess of 10 percent or 100 000 megawatt days per metric ton are possible with diametral growth less than 1 percent in 10 000 hours. Fission densities in the range of 10^{20} to 10^{21} fissions per cubic centimeter of total pin volume are conservatively predicted.

The vapor-transport feature of this concept causes redistribution of reactor fuel to occur. This redistribution tends to accommodate and relieve the adverse effects of nonuniform power distribution, hot spots, and nonuniform burnup. For any given fuel burnup the change in reactor reactivity is reduced when compared with fuel pins where fuel redistribution is prevented.

INTRODUCTION

The life of almost all high-power, long-life reactors is limited by the life of the fuel elements. The lifetime of fuel elements is generally limited by failure caused by swelling of the fuel material or release of fission gases, which generate high pressures within the fuel. The swelled fuel, or high fission-gas pressure, then causes excessive growth or rupture of the fuel-cladding material. Normal practice allows for some swelling, about 1 or 2 percent. This amount of swelling occurs when fuel burnup (in atoms fissioned for heavy atoms present) reaches about 1 to 3 percent. Burnups in the range of 5 to 10 percent are considered to be unusually high.

It is the purpose of this report to present and describe the very-high-burnup, vapor-transport fuel concept. This concept eliminates problems of fuel swelling and fission-product release by design. The procedure is conservative and simple. The design principles can be derived from previous observations of fuel behavior (refs. 1 to 6). For example, it has been noted that voids in fuel tend to migrate (ref. 1). This migration occurs because fuel vaporizes from the hot side of a void and condenses on the cooler side. The void, therefore, appears to move up the temperature gradient. This same phenomenon causes central voids to form in bulk uranium dioxide (UO_2) fuel pins. It is also responsible for large fuel movements from one part of a fuel pin to another. This effect, in general, has been treated as a difficulty to be avoided. It has also been recognized that providing void regions for collection of fission gases reduces swelling caused by fission-gas pressure (refs. 2 and 3). It is obvious that in order to minimize stress in the cladding due to mechanical interaction with the fuel, the cladding should be designed to be stronger than the fuel (refs. 3, 4, and 6). The fuel pin proposed in this report takes advantage of these phenomena to produce a concept that permits rational prediction of fuel burnups an order of magnitude higher than currently considered acceptable. With such high burnups, the vapor-transport fuel pin has the potential for (1) increasing the operating life of reactor fuel and thus decreasing the operating cost of nuclear powerplants, (2) increasing the power density of power reactors for any desired core life with a consequent reduction in capital cost due to a more compact installation, and (3) making possible very compact high-power, long-life mobile reactors where minimization of shield weight is important.

SYMBOLS

A fission-gas atoms released per fuel atom fissioned

A_v Avagodro's number, atoms/g-mole

B fraction of fissionable fuel atoms fissioned, (atoms U^{235} fissioned)/(total initial U^{235} atoms)

$\overline{B}$ generalized burnup parameter (see table I)

B' fuel atoms fissioned per total pin volume, atoms fissioned/cm^3

$\overline{B}'$ generalized fission density parameter (see table I)

C void- to fuel-volume ratio

d diameter of tube, cm

d_f fuel-zone outer diameter, cm

d_i fuel-zone inner diameter, cm

E ratio of fuel volume to total pin volume

e enrichment, (total initial U^{235} atoms)/(all initial U atoms)

F function of t/d and t_f/t as given in eq. (18)

G generalized overall performance parameter (see table I)

K_1 ratio of energy release per fission, kW-sec/fission (3.2×10^{-14})

k_u thermal conductivity of fuel, kW/(cm)(K)

L fuel-pin lifetime, sec

n_g fission-gas atom density, atoms/cm^3

n_u fuel density (atoms of fissionable material per fuel volume), atoms/cm^3 (2.436×10^{22} for UO_2)

P pressure, g/cm^2

$\overline{P}$ generalized pressure parameter (see table I)

$\overline{Q}$ generalized heat-flux parameter (see table I)

Q'' fuel-pin surface heat flux, kW/cm^2

R gas constant, g-cm/(K)(g-mole) (8.49×10^4)

T inside fuel-surface temperature, K

T_s fuel-pin surface temperature, K

t thickness of tube wall, cm

t_f fuel thickness, cm

σ allowable hoop stress, g/cm^2

DESCRIPTION OF VAPOR-TRANSPORT FUEL-PIN CONCEPT

The vapor-transport fuel pin is simply a tube sealed at both ends that contains a thin layer of fuel and a large void space, as shown in figure 1. The fuel that covers the inside surface of the tube is thin enough so that it cannot exert significant forces on the tube through thermal expansion or swelling. The only major force that the tube experiences is that caused by the difference in pressure across the tube wall. It is assumed that thermal stresses in the tube wall are negligible compared with the stress produced by the fission-gas pressure at end of life.

The large void volume allows room for fission-product gases that escape from the fuel. The burnup limit of the fuel pin is determined when the tube can no longer contain the pressure that is built up by the fission gases without exceeding desired strain limits. In general, the thicker or the stronger the tube walls, the higher will be the burnup limit. Also, the larger the void volume fraction, the higher the burnup limit.

A special feature of this fuel pin is that fuel redistribution by vapor transport is permitted by design. This feature is desired rather than avoided. By design the fuel thickness for any particular application can be selected to produce an inside-fuel-surface temperature high enough to yield significant vapor pressure. The inside fuel surface will therefore tend toward operation at a constant temperature independent of all operating conditions external to the fuel. Hot spots in the fuel, for example, are automatically eliminated by fuel vaporization from the hot zone. Likewise, cold spots are eliminated by selective condensation of fuel vapor onto the regions that would tend to run cooler. The equilibrium fuel-thickness distribution automatically reverts to that which produces a uniform inside-fuel-surface temperature. The rate at which equilibrium conditions (and, hence, isothermal fuel-surface conditions) are attained following a perturbation is a function of the design fuel-surface temperature (fuel vapor pressure). The higher the temperature, the faster equilibrium will be reached. The important implications of the vapor-transport feature are discussed in a subsequent section of this report.

ANALYSIS

The design analysis for the vapor-transport fuel pin is simple. The tube wall is considered to be a pressure vessel whose only function is to contain the released-fission-gas pressure at the design operating temperature and lifetime desired. The stresses in the tube wall due to fuel swelling should by design be negligible compared with the hoop stress produced by the fission-gas pressure. The fuel must therefore be thin enough in comparison to the tube wall so that stresses introduced by differential expansion or fuel swelling are relieved by plastic flow of the fuel without introducing large stresses in the tube wall. It is desirable, therefore, that the tube wall be made of materials with high tensile strength when compared with the compressive strength of the fuel material. Figure 2 shows the allowable stress for 1 percent creep in 10 000 hours for several materials as a function of temperature, to illustrate this point. The curves for uranium nitride (UN) and UO_2 are estimated compressive creep strengths (ref. 7). Molybdenum has a strength about 4 to 10 times that of UN and UO_2. The fuel could therefore be as thick or thicker than the fuel-pin wall without having an appreciable effect on the wall stress. In the case of stainless steel, the fuel thickness would probably have to be less than the tube-wall thickness. It is beyond the scope of the report to determine precisely the allowable values of fuel- to wall-thickness ratio for particular materials.

The fission-gas pressure is determined by the amount of fission gases released, the temperature of the fission gases, and the void volume available within the pin. The amount of fission gases released depends on the fuel temperature, the temperature gradient, and the amount of fuel that is burned up. The exact dependence of fission-gas release on these quantities has not been, and probably cannot be, well defined for several reasons. In any practical situation, large temperature variations exist across the fuel region because the energy is removed from the surface while it is generated throughout the fuel volume. In addition, energy is not generated uniformly in the fuel region because of attenuation of the neutron flux across the fuel. The precise flux attenuation and, hence, power and temperature distribution is therefore a function of the fuel thickness and the neutron energy spectrum. The selective diffusion of fission products through the fuel could also affect the local release of gases. For example in the case of UO_2, it would be expected that all fission products that are normally gases or vapors, with the exception of the inert fission gases, would probably react with either the fuel, the oxygen that is liberated when a uranium atom is fissioned, or other fission products that are generated. The authors recommend that 100 percent of the noble gases should be assumed to escape to the void space. Since it is not likely that 100 percent of the noble gases do escape, the authors believe that the above recommendation should lead to a conservative fuel-pin design. This conservatism would compensate for some of the unknowns in the design, such as the effect of fission products and radiation on cladding properties and the contribution of any noninert fission gases to the fission-gas pressure.

The temperature of the fission gases is assumed to be equal to the inside surface temperature of the fuel since there would be essentially no energy liberated within the gas. The inside-fuel-surface temperature is a design variable that is selected by the fuel-pin designer.

The remaining quantity needed to determine the fission-gas pressure is the volume of the void that is available for the fission gases. Again, this is a design variable that is selected by the fuel-pin designer. The larger the available void space, the slower will be the rate of fission-gas pressure buildup, the higher will be the allowable burnup fraction, and the longer will be the life of the fuel pin. The additional void volume required for long-life fuel pins can be obtained in some cases by using more highly enriched fuel. This, in effect, replaces the nonfissionable heavy atoms with void. In other cases, the extra void must come at the expense of extra reactor volume. The optimum fuel-pin void volume is a function of the particular application and the criteria that determine the best compromise for each reactor. It is beyond the scope of this report to consider possible applications and the criteria for optimization of fuel pins for these applications.

The relations between the basic fuel-pin variables, such as diameter, wall thickness, fuel thickness, heat flux, burnup, lifetime, allowable hoop stress, inside fuel temperature, fuel-pin temperature, fractional gas release, fission density, and fuel pressure, are derived in the following analysis. It is shown that the generalized performance parameters in table I can be used to relate all these variables.

TABLE I. - GENERALIZED PERFORMANCE PARAMETERS

Generalized parameter	Symbol	Definition
Pressure	$\overline{P}$	$\frac{P}{\sigma}$
Burnup	$\overline{B}$	$\frac{BTAn_u e}{\sigma}$
Fission density	$\overline{B}'$	$\frac{B'TA}{\sigma}$
Heat flux	$\overline{Q}$	$\frac{Q''LAT}{d\sigma}$
Overall performance	G	$\frac{LAT(T - T_s)k_u}{d^2\sigma}$

Generalized Pressure Parameter

The relation between fission-gas pressure, tube diameter, tube wall thickness, and allowable hoop stress is determined by the hoop stress equation

$$P(d - 2t) = 2t\sigma$$

which can be reduced to

$$P = \frac{2\sigma \frac{t}{d}}{1 - 2\frac{t}{d}} \tag{1}$$

It should be recognized that the actual stress in the tube wall is, in the general case, not the same as the hoop stress. This is especially true for thick-wall tubes where stresses have not been relieved by creep. In using the curves of this report, the hoop stress that gives the maximum actual allowable stress is the stress that should be used.

In terms of generalized pressure P/σ, equation (1) becomes

$$\overline{P} = \frac{P}{\sigma} = \frac{2\frac{t}{d}}{1 - 2\frac{t}{d}} \tag{2}$$

The generalized pressure parameter $\overline{P}$ is plotted in figure 3 as a function of t/d.

Generalized Burnup Parameter

The relation between fission-gas pressure, fuel-surface temperature, fuel-pin volume, and fission-gas atoms released is derived as follows. The perfect gas law gives

$$P = \frac{n_g RT}{A_v} \tag{3}$$

where n_g is the number of fission-gas atoms per void volume and is given by

$$n_g = \frac{n_u ABe}{C} \tag{4}$$

where n_u is the atom density of fuel (uranium atoms divided by fuel volume), A is the number of fission-gas atoms released per fission, B is the fraction of the total fuel atoms fissioned, e is the U^{235} enrichment, and C is the void- to fuel-volume ratio. It should be recognized that the burnup fraction B as defined herein does not include non-fission neutron absorption by the fissionable isotope. The loss of fissionable isotope is increased by about 20 percent because of this effect. The exact amount is a function of the neutron spectrum to which the fuel is exposed. In terms of tube diameter, wall thickness, and fuel thickness,

$$C = \frac{(d - 2t - 2t_f)^2}{(d - 2t)^2 - (d - 2t - 2t_f)^2} \tag{5}$$

or in terms of t/d and t_f/t

$$C = \frac{\left(1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}\right)^2}{\left(1 - 2\frac{t}{d}\right)^2 - \left(1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}\right)^2} \tag{6}$$

Setting the allowable pressure equal to the pressure produced and using equations (1), (3), and (4) give

$$\frac{2\sigma\frac{t}{d}}{1 - 2\frac{t}{d}} = \frac{n_u ABRTe}{A_v C}$$

Rearranging terms to find the allowable fuel-burnup fraction B gives

$$B = \frac{2\sigma\frac{t}{d} A_v C}{en_u\left(1 - 2\frac{t}{d}\right)ART} \tag{7}$$

In terms of generalized burnup $\overline{B}$ equation (7) becomes

$$\overline{B} = \frac{BTAn_u e}{\sigma} = \frac{2A_v C\frac{t}{d}}{R\left(1 - 2\frac{t}{d}\right)} \tag{8}$$

The generalized burnup parameter $\overline{B}$ is plotted in figure 4 as a function of t/d and t_f/t.

Generalized Fission Density Parameter

Another useful method of describing or evaluating fuel-pin performance is in terms of allowed fission density B' which is defined as the number of fissions allowed per total pin volume. The following equation relates B' to the fuel-burnup fraction B:

$$B' = Bn_u Ee \tag{9}$$

where E is the ratio of fuel volume to total pin volume

$$E = \frac{(d - 2t)^2 - (d - 2t - 2t_f)^2}{d^2}$$

or

$$E = \left(1 - 2\frac{t}{d}\right)^2 - \left(1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}\right)^2 \tag{10}$$

Combining equations (7) and (9) gives the following expression for allowable fission density in fissions per cubic centimeter of total pin volume

$$B' = \frac{2\sigma\frac{t}{d}A_v CE}{\left(1 - 2\frac{t}{d}\right)ART} \tag{11}$$

In terms of generalized fission density $\overline{B'}$ equation (11) becomes

$$\overline{B'} = \frac{B'TA}{\sigma} = \frac{2A_v CE\frac{t}{d}}{R\left(1 - 2\frac{t}{d}\right)} \tag{12}$$

The generalized fission density parameter $\overline{B'}$ is plotted in figure 5 as a function of t/d and t_f/t. The plot of the generalized burnup parameter which is used to obtain the fission density in terms of total fissions per total volume of fuel pin shows that for each value of fuel-thickness to tube-wall-thickness ratio there is a value of tube-wall-thickness to diameter ratio that yields a maximum fission density.

Generalized Heat-Flux Parameter

The allowable fuel-pin fission density and desired lifetime of the pin determine the pin surface heat flux Q'' (kW/cm^2)

$$Q'' = \frac{K_1 B'}{L} \times \frac{\text{Volume of fuel pin}}{\text{Surface area of pin}} \tag{13}$$

where K_1 is the energy release rate per fission in kilowatt-seconds per fission, and L is the fuel-pin lifetime in seconds. The ratio of fuel-pin volume to surface area is

$$\frac{\text{Fuel-pin volume}}{\text{Fuel-pin surface area}} = \frac{d}{4}$$

Therefore,

$$Q'' = \frac{K_1 B' d}{4L} \tag{14}$$

Using equation (11) to obtain the relation for B' and rearranging terms gives the generalized heat-flux parameter $\overline{Q}$

$$\overline{Q} = \frac{Q''LAT}{d\sigma} = \frac{K_1 A_v CE \frac{t}{d}}{2R\left(1 - 2\frac{t}{d}\right)} \tag{15}$$

The generalized heat-flux parameter $\overline{Q}$ is plotted in figure 6 as a function of t/d and t_f/t.

Generalized Overall Performance Parameter

In order to relate surface heat flux to the inside-fuel-surface temperature and fuel thickness, the following equation, which gives the relation between pin surface heat flux, inside-fuel-surface temperature, pin surface temperature, pin and fuel dimensions, and thermal conductivity of the fuel, can be derived (see ref. 8). It is assumed that the conductivity of the fuel-pin tube material is large compared with the fuel conductivity and that the volumetric heat generation is uniform within the fuel region.

$$T - T_s = \frac{Q''d\left(d_f^2 - d_i^2 + 2d_i^2 \ln \frac{d_i}{d_f}\right)}{4k_u\left(d_f^2 - d_i^2\right)} \tag{16}$$

Since $d_f = d - 2t$ and $d_i = d - 2t - 2t_f$ equation (16) can be rewritten as follows:

$$T - T_s = \frac{Q''dF}{4k_u} \tag{17}$$

where

$$F = 1 + \frac{2 \ln \dfrac{1 - 2\dfrac{t}{d} - 2\dfrac{t_f}{t}\dfrac{t}{d}}{1 - 2\dfrac{t}{d}}}{\left(\dfrac{1 - 2\dfrac{t}{d}}{1 - 2\dfrac{t}{d} - 2\dfrac{t_f}{t}\dfrac{t}{d}}\right)^2 - 1} \tag{18}$$

Combining equations (17) and (14) gives

$$T - T_s = \frac{K_1 B' d^2 F}{16 L k_u} \tag{19}$$

Combining equation (19) with equation (11) gives

$$T - T_s = \frac{K_1 A_v \sigma d^2 C E F\left(\dfrac{t}{d}\right)}{8 k_u R A T L \left(1 - 2\dfrac{t}{d}\right)} \tag{20}$$

which gives finally the expressions for fuel lifetime in terms of the fuel-pin variables

$$L = \frac{K_1 A_v d^2 \sigma C E F\left(\dfrac{t}{d}\right)}{8 k_u R A T (T - T_s)\left(1 - 2\dfrac{t}{d}\right)} \tag{21}$$

Grouping all quantities on the right side which are constants or functions of t/d and t_f/t gives the following generalized overall performance parameter G

$$G = \frac{LAT(T - T_s)k_u}{d^2\sigma} = \frac{K_1 A_v CEF \frac{t}{d}}{8R\left(1 - 2\frac{t}{d}\right)} \tag{22}$$

To obtain G exclusively in terms of t/d and t_f/t equations (18), (10), and (6) are substituted into equation (22), which then gives

$$G = \frac{LAT(T - T_s)k_u}{d^2\sigma} = \frac{K_1 A_v \frac{t}{d}\left(1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}\right)^2}{8R\left(1 - 2\frac{t}{d}\right)} \left[1 + \frac{2 \ln \dfrac{1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}}{1 - 2\frac{t}{d}}}{\left(\dfrac{1 - 2\frac{t}{d}}{1 - 2\frac{t}{d} - 2\frac{t_f}{t}\frac{t}{d}}\right)^2 - 1}\right] \tag{23}$$

The generalized overall performance parameter G is plotted in figure 7 as a function of tube-wall-thickness to tube-diameter ratio t/d for a range of values of fuel-thickness to tube-wall-thickness ratio t_f/t. It should be recalled that the volumetric heat generation rate is assumed to be constant within the fuel and that the temperature drop across the tube wall is negligible compared with the temperature drop across the fuel. While this curve is calculated for constant volumetric heat generation and neglects the temperature drop through the fuel-pin wall, any desired heat generation distribution and pin-wall thermal conductivity could be chosen. This curve could then be recalculated for the new assumptions. Actual heat generations generally fall off toward the center of the pin. A pin with such a nonuniform power distribution would operate with a lower inside-fuel-surface temperature T than predicted from figure 7. The actual fuel pin would therefore have a longer lifetime than a pin with uniform heat generation because the fission-gas pressure would be smaller at the lower temperature. Since power generation always falls off toward the center of actual pins, the curve of figure 7 will always give a conservative performance estimate.

USE OF GENERALIZED PERFORMANCE CHARTS

The generalized performance parameters presented in figures 3 to 7 merely represent the interrelation among all the 12 fuel-element variables. These variables are

(1) Tube outside diameter, d, cm
(2) Tube-wall-thickness to diameter ratio, t/d
(3) Fuel-thickness to wall-thickness ratio, t_f/t
(4) Allowable wall hoop stress, σ, g/cm^2
(5) Inside-fuel-surface temperature, T, K
(6) Tube-wall temperature, T_s, K
(7) Lifetime, L, sec
(8) Gas release to the void, A, atoms per fission
(9) Fuel-pin surface heat flux, Q'', kW/cm^2
(10) Fuel-pin fission density, B', atoms fissioned/cm^3 of total pin volume
(11) Burnup fraction, B, fraction of U^{235} atoms fissioned
(12) Fission-product gas pressure, P, g/cm^2

Any seven of these twelve variables is sufficient to completely determine the remaining five. The values are determined by the use of the generalized parameters plotted in figures 3 to 7. To illustrate the use of these figures a typical set of seven variables is assigned. The procedure for finding the remaining five is then outlined.

Consider the case where A, T, T_s, d, σ, and t_f/t are specified and a certain lifetime L is desired. The value of A (gas fission products released per fission) is assigned. The designer may select the value of A based on his best judgment, experience, or interpretation of data. The authors recommend using a value of 0.25 based on the data presented in reference 9. The fuel-pin surface temperature may be selected to meet a specific heat-transfer requirement. (It should be recognized that the allowable hoop stress is strongly affected by the tube temperature and, therefore, may be just as important in selecting a temperature as is meeting a heat-transfer requirement.) The inside-fuel-surface temperature is selected on the basis of the need or desirability of vapor transport within the fuel pin. The pin diameter may be selected by heat transfer or structural requirements. The allowable hoop stress is assigned to be consistent with the tube material, the tube operating temperature, the assigned lifetime, and the allowable deflection. The allowable hoop stress is defined as that hoop stress which gives the allowable maximum actual stress in the tube wall. The ratio of fuel thickness to tube-wall thickness t_f/t is selected to meet the requirement that the fuel be thin enough so that it does not add any undesirable stress to the tube wall in addition to the hoop stress caused by fission-gas pressure. Having selected the values of the above seven variables, the designer can now calculate the value of G that is plotted in figure 7. At this value of G and the selected t_f/t, a value of t/d can be determined from figure 7. At this value of t/d and the selected t_f/t, values of the parameters $\overline{Q}$, $\overline{B}$, $\overline{B}'$, and $\overline{P}$ can be determined from figures 3 to 6. Each of these parameters can be reduced by use of the assigned variables to yield Q'', B', B, and P.

Specific examples for the use of the generalized performance parameters appear in appendixes A and B. Appendix A deals with a sample molybdenum fuel pin designed for 10 000-hour operation with a wall temperature of 1500 K (2240° F). Appendix B considers a sample stainless-steel fuel pin for operation at 1000 K (1340° F) for 10 000 hours. The results of these calculations are summarized in table II.

TABLE II. - SAMPLE MOLYBDENUM-FUEL-PIN

PERFORMANCE SUMMARY

Parameter	Fuel pin	
	Molybdenum	Stainless steel
Pin outside diameter, d, cm	1.628	2.14
Pin wall thickness, t, cm	0.2442	0.321
Fuel thickness, t_f, cm	0.1221	0.0963
Design lifetime, L, sec (10 000 hr)	3.6×10^{7}	3.6×10^{7}
Pin wall temperature, T_s, K	1500	1000
Inside-fuel-surface temperature, T, K	2500	2500
Allowable hoop stress (1 percent creep in 10 000 hr), σ, g/cm^2	4.22×10^{5}	5.07×10^{5}
Fuel- to tube-wall-thickness ratio, t_f/t	0.50	0.30
Tube-wall-thickness to diameter ratio, t/d	0.15	0.15
Fission density, B', total fissions/cm^3 of total pin	6.20×10^{20}	9.22×10^{20}
Fuel burnup fraction, B, fraction of total U	0.1445	0.343
Burnup, megawatt days/metric ton of U	121 500	286 000
Fuel-pin surface heat flux, Q'', kW/cm^2	0.224	0.44

DISCUSSION

A very-high-burnup, vapor-transport fuel-pin concept has been presented which is relatively simple to design. The pin is essentially a sealed tube with a thin internal lining of a fuel material. The tube wall is designed to withstand the released-fission-gas pressure. The fuel lining is made thin enough so that the stress it can produce in the tube is negligible when compared with the stress produced by the fission-gas pressure. The temperature of the inside surface of the fuel is a design variable. By design the inside-fuel-surface temperature can be made high enough so that vapor transport of the fuel will occur. In this way the fuel thickness will vary automatically so as to maintain a constant inside-fuel-surface temperature. The void volume within the fuel pin is made sufficiently large to provide room for the fission gases which are released from the fuel.

Using these principles the fuel pin can be designed to operate at any desired value of fuel burnup. The only limitation is the ability to design a reactor that can accommodate large burnups.

Curves have been presented which facilitate the rough design of fuel pins using these principles.

Fission-Gas Release Assumption

In the use of the curves it is necessary to specify the number of gas atoms released into the pin void per fission. The authors recommend that it be assumed that all the inert gas fission products are released to the void. It is also recommended that all other fission products or the compounds they form be assumed to have a negligible vapor pressure. This is probably a good assumption especially for the case of UO_2. In this case two oxygen atoms are released for each two fission-product atoms. In addition to the likely formation of oxides there are many possible compounds that can be formed among the fission products themselves. The authors believe that the assumption of 100 percent inert-fission-gas release for determining fission-gas pressure is conservative.

Novel Pin Characteristics

In past fuel-pin designs the natural tendency for fuel to transfer has generally been considered as a phenomenon to be avoided. There are several research programs whose chief goal is to prevent such transfer. The authors' position is that the fuel should be allowed to move. Advantage should be taken of this phenomenon that nature has provided. It is our position that the use of fuel pins that allow redistribution of fuel by vapor transport will make reactor design simpler and, in addition will provide superior overall reactor performance. In the following discussion some of the consequences of designing fuel pins to permit free movement of the fuel are pointed out.

Hot spots relieved. - Allowing the fuel to move by vapor transport relieves the problem of fuel-pin hot spots. No matter what causes the hot spot (e.g., poor initial fuel distribution, local heat-transfer difficulty, local flow perturbation, local neutron-flux perturbation, etc.) the fuel in the region of the hot spot will selectively evaporate and then condense in cooler regions of the pin. The amounts evaporated and condensed will automatically occur in precisely the right amounts to produce an isothermal inside fuel temperature. Thus, a region where a hot spot would normally have occurred is now a region with less heat generation because of the local thinning down of the fuel. The rate at which hot spots are removed is controlled by the design inside-fuel-surface temperature; the hotter the fuel, the faster the response.

The use of the vapor-transport fuel pin thus reduces the ratio of the maximum to average temperature and the variation of temperature throughout the fuel-pin life. This, of course, means greater margins or increased fuel reliability and life.

Lower fission-gas pressure. - In the subject fuel-pin concept the gaseous fission products are uniformly distributed over the entire fuel-pin length. The fission-product pressure is thus the average pressure regardless of the burnup distribution along the length of the fuel. If the gases were not allowed to vent through the entire fuel-pin length, the local fission-gas pressure at the point of highest power generation would be higher than the average. The life of the pin would thus be limited to the life of the portion of the pin with the highest burnup. (The life is defined as the time when the fission-gas pressure exceeds the capability of the fuel-pin tube to hold it.) The fuel pin would permit increases in fuel-pin life by 30 percent, for example, for reactors with peak-to-average axial burnups of 1.3. This feature of the fuel pin occurs whether vapor transport of fuel is included in the design or not.

Less effect of burnup on reactivity. - In most reactors fuel burnup occurs at a higher rate near the center of the core or in any region where the neutron flux is higher than the average. If vapor transport is included in the design, the fuel that is burned up locally at a higher rate than the average is replenished with fuel from the remainder of the pin. This occurs because the local higher burnup rate tends to reduce local power with time with an attendant reduction in inside-fuel-surface temperature. Since the overall power must be held constant, lower burnup regions will have a tendency to increase in power with an increase in inside-fuel-surface temperature with time. Fuel will therefore transfer from the lower burnup regions to the higher burnup regions as time progresses. Thus, fuel tends to move from the low neutron-flux zones to the higher neutron-flux zones as the fuel is burned up. Nothing could be more ideal from the point of view of minimizing reactivity change with core life. Fuel from the regions of least reactivity worth (low neutron-flux regions) is transported automatically to the regions of maximum reactivity worth as the fuel is burned up. And this occurs while the pin inside-fuel-surface temperature automatically remains isothermal.

It seems clear that this feature should greatly relieve the problem of reactivity control for long-life reactors while at the same time greatly simplifying heat-transfer design because of the automatic relief of hot spots. For any given allowable reactivity change over the lifetime of a reactor, a fuel pin with vapor transport will allow longer reactor life.

Many fuel and tube materials can be used. - The fuel pin can be constructed of many suitable fuels and tube materials. The tube material must be compatible chemically with the selected fuel material and the desired reactor coolant. It should be a high-strength material at the desired operating temperature so that the maximum fission-gas pressure can be contained for long-life operation. Ideally, the tensile strength of the tube material should be high relative to the compressive strength of the fuel so that the fuel exerts the least possible force on the cladding as it expands and deforms as a result of fission-product buildup and temperature changes in transient operation. Thus, stainless-steel tubes with fuels such as UO_2, plutonium oxide (PuO_2), mixed UO_2 and PuO_2, or UN could be used for reactors which use water or air as coolants. Refractory-metal tubes with any compatible fuel can be used for high-temperature, inert-gas- or liquid-metal-cooled reactors.

A variety of physical forms of fuel can be used. - The fuel for the fuel pin can be in any preferred initial form, such as pellets (high or low density), beads, granules, marbles, or powder, and can be made by any process, for example, hot pressing, cold pressing, casting, or sintering. No matter what the initial form and distribution of the fuel within the pin, it will always end up coating the inside surface of the fuel tube with exactly the right thickness distribution to produce the design isothermal inside-surface temperature. This point is illustrated in figure 8. The first view shows a fuel-pin tube with UO_2 or any other fissionable material in any arbitrary form in any arbitrary location within the tube. The second view illustrates vaporization of the fuel caused by fission heating. The vaporized fuel is shown condensing on the cold walls of the tube where there was no fuel. The fuel continues to vaporize from the original fuel region and deposits on the cooler surfaces where there is less fuel until an equilibrium is reached. This occurs when the inside-fuel-surface temperature is uniform all over. If the rate of heat removal and the external coolant temperature are uniform, the thickness of the fuel inside the pin will be uniform. If the heat removal rate or the coolant temperature is nonuniform, the fuel thickness will not be uniform. It will automatically adjust to just the right thickness variation to produce a uniform inside-surface temperature.

It may be needless or undesirable from a practical point of view to design a reactor that can accept pins with randomly distributed fuel that will coat the walls of the fuel pins during reactor startup. It is important to note, however, that even this extreme is possible from the point of view of the fuel. The important implication is that the designer is free to choose from a vast number of possible initial fuel forms and manufacturing processes. This flexibility should produce a saving in the cost and time for fuel recycling because of the large variety of fabrication techniques that the designer can select from.

Higher surface heat flux permitted. - High-heat-flux pins of any diameter are possible when the proposed fuel-pin concept is used. This is made possible by virtue of the relatively thin fuel region of these pins. The surface heat-flux capability of a pin is determined chiefly by the thickness of the fuel rather than of the tube or cladding. The fuel usually has a low thermal conductivity, and, consequently, the major temperature drop occurs in the fuel. This may not be true in certain exceptions, such as a stainless-steel pin with thin UN fuel. In such cases the tube-wall temperature drop must be considered.

The fuel temperature drop together with its thickness and maximum allowable temperature determines the heat flux. In conventional fuel pins the fuel is thick compared with the cladding. The pin must therefore be small in diameter to produce a high surface heat flux without exceeding the melting point of the fuel at the center. The higher heat-flux capability of the subject fuel-pin concept would probably show up in the form of reduced fuel manufacturing cost because fewer of the larger fuel pins would be required for any given desired reactor power output.

Potential Problem Areas

The greatest potential problem area is the one of life prediction. With the procedures that are recommended, the authors believe that fuel life will be conservatively estimated. The fuel would be expected to have a life longer than predicted. The precise determination of fuel life beyond this estimation will require experimental investigation. An area of concern particularly where burnups are high, greater than 10 percent and maybe higher than 50 percent, is that the fuel-pin contents may be composed chiefly of fission products and compounds of them. Some of the many compounds formed may diffuse to the tube wall and may cause chemical compatibility problems. Also, the long-life fuel made possible by this concept may create the problem of radiation effects on the tube material properties. Fission-product recoil into the tube material, with subsequent decay and further exposure to neutrons, may form harmful elements or compounds within the tube walls.

In most applications for long-life reactors the fuel-pin concept introduces significant void space into the reactor, which, in general, would be expected to increase the total core volume. In some cases, however, the void may replace nonfissionable material which has been eliminated by using a higher initial fuel enrichment. In addition, in other cases the high heat-flux capability of the fuel may permit an overall reduction in core size which balances against the increased void. Whether the additional void offsets the other advantages of the fuel pin is a matter that can only be determined by a study for the particular application.

Another problem area that is introduced by the use of a fuel pin with much greater life potential than conventional fuel pins is one of reactor reactivity control. Reactor life may now no longer be limited by fuel-pin limitations but by the ability to design reactors with large reactivity changes. Even though the vapor-transport fuel pin greatly reduces the reactivity change for a given reactor lifetime, the fuel pin now permits even greater reactor life so that eventually reactivity control may be the limiting factor. The full potential of the vapor-transport fuel concept may not be useable unless control-system concepts are developed to handle its full potential.

Sample Calculations

Sample calculations were made to illustrate the use of the suggested fuel-pin design procedures. The calculations incidentally illustrate the potential of this fuel-pin concept.

Table II, which summarizes the sample molybdenum fuel pin, indicates the capability of a fission density of 6.20×10^{20} fissions per cubic centimeter of total pin volume. The corresponding burnups in fraction of U atoms burned up and in megawatt days per metric ton of U atoms are 0.1445 and 121 500, respectively. The corresponding values of fuel-pin diameter and heat flux are 1.628 centimeters (0.641 in.) and 0.224 kilowatt per square centimeter (1.446 kW/in.^{2} or 708 000 Btu/hr-ft^2), respectively. This design is quite conservative because the design procedure assumes that the fission-gas pressure at end of life existed for the entire 10 000 hours. The actual diametral swelling would therefore be less than 1 percent, which is calculated by assuming that the final pressure stress exists in the wall for the entire life of the pin.

Table II, which also summarizes the sample 10 000-hour stainless-steel fuel pin, indicates the possibility of conservatively predicting fission densities of close to 10^{21} fissions per cubic centimeter. The diametral swelling actually would be less than the calculated 1 percent. The corresponding values of fuel burnup expressed in fraction of total U atoms and megawatt days per metric ton of U atoms are 0.343 and 286 000, respectively. The pin diameter for this sample case is 2.14 centimeters (0.843 in.). The heat flux is 0.44 kilowatt per square centimeter (2.84 kW/in.^{2} or 1 395 000 Btu/hr-ft^2). The operating temperature of this pin is 1000 K (1340° F); lowering the fuel-pin wall temperature would improve its performance considerably because of the increase in strength of the tube wall. The limitation of the application of this fuel pin would eventually be determined by criticality of the reactor core.

CONCLUSIONS

In this analysis of the very-high-burnup, vapor-transport fuel-pin concept, the following conclusions were reached:

1. The fuel-pin concept makes it possible to design reactor fuel pins that in the authors' opinion will conservatively achieve burnups and fission densities well in excess of current practice.

2. The fuel pin has the ability to relieve hot spots, average out axial fission-gas-pressure buildup, and minimize reactor reactivity changes for long-life reactors.

3. The fuel-pin concept can be applied to a large variety of tube materials, fuels, and fuel forms.

4. A sample molybdenum fuel pin with a diameter of 1.628 centimeters (0.641 in.)

and which was designed for operation with a tube-wall temperature of 1500 K (2240° F) can be expected to have a burnup of 14.5 percent of the uranium atoms and operate for a period of 10 000 hours with a surface heat flux of 0.224 kilowatt per square centimeter.

5. A sample stainless-steel fuel-pin calculation for operation with a tube-wall temperature of 1000 K (1340° F) indicated that the pin was capable of burnups of 34.3 percent of the uranium atoms (286 000 megawatt days per metric ton) while operating for 10 000 hours. The pin diameter for this case was 2.14 centimeters and had a heat flux of 0.44 kilowatt per square centimeter.

6. The previous uncertainty in fuel-pin performance prediction can be eliminated by the use of the vapor-transport fuel pin. One of the features of the pin is to set the fuel thickness thin enough so that no matter what happens to the fuel (swelling, expansion, plastic flow, etc.) it cannot produce a significant stress in the tube wall. Pin life is therefore simply determined by fission-gas-pressure buildup, rather than by the complex and poorly understood phenomenon of fuel swelling.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 23, 1968,
126-15-01-03-22.

APPENDIX A

SAMPLE MOLYBDENUM-FUEL-PIN CALCULATION

For a molybdenum fuel pin the fuel-pin diameter, the fission density in total fissions per total pin volume, the burnup fraction, the heat flux, and the internal pressure at the end of life were calculated for the following assigned operating conditions:

Lifetime, L, sec (10 000 hr)	3.6×10^7
Inside-fuel-surface temperature, T, K	2500
Tube-wall temperature, T_s, K	1500
Allowable tube-wall hoop stress, σ, g/cm^2	4.22×10^5
Fuel-thickness to tube-wall-thickness ratio, t_f/t	0.5
Tube-wall thickness to diameter ratio, t/d	0.15
Gas atoms released per fission, A	0.25
Enrichment, e	0.93

The values for G, $\overline{B'}$, $\overline{B}$, $\overline{Q}$, and $\overline{P}$ are found from figures 3 to 7 for the values of t_f/t and t/d assigned.

$$G = \frac{LAT(T - T_s)k_u}{d^2\sigma} = 403$$

$$\overline{B'} = \frac{B'AT}{\sigma} = 9.18\times10^{17}$$

$$\overline{B} = \frac{BATN_u}{\sigma} = 4.88\times10^{18}$$

$$\overline{Q} = \frac{Q''LAT}{d\sigma} = 7.34\times10^{3}$$

$$\overline{P} = \frac{P}{\sigma} = 0.4286$$

From the value of G and its definition the fuel-pin diameter can be found as follows:

$$d^2 = \frac{LAT(T - T_s)k_u}{G\sigma} = \frac{3.6\times10^7 \times 0.25 \times 2500\ (2500 - 1500) \times 2\times10^{-5}}{403 \times 4.22\times10^5}$$

$$d^2 = 2.65$$

$$d = 1.628 \text{ cm}$$

From $\overline{B}'$ and its definition the average fission density over the entire pin volume and for the whole life of the pin can be found.

$$B' = \frac{\overline{B}'\sigma}{AT} = \frac{9.18\times10^{17} \times 4.22\times10^5}{0.25 \times 2500}$$

$$B' = 6.20\times10^{20} \text{ fissions/cm}^3$$

From the value of B and its definition the fraction burnup of the heavy fuel atoms can be found.

$$B = \frac{\overline{B}\sigma}{ATn_u e} = \frac{4.88\times10^{18} \times 4.22\times10^5}{0.25 \times 2500 \times 2.436\times10^{22} \times 0.93}$$

$$B = 0.1455 \frac{\text{U atoms fissioned}}{\text{Total U atoms present}}$$

From the value of $\overline{Q}$ and its definition the fuel-pin surface heat flux can be found.

$$Q'' = \frac{\overline{Q}d\sigma}{LAT} = \frac{7.34\times10^3 \times 1.628 \times 4.22\times10^5}{3.6\times10^7 \times 0.25 \times 2500}$$

$$Q'' = 0.224 \text{ kW/cm}^2 = (1.446 \text{ kW/in.}^2)$$

From the value of $\overline{P}$ and its definition the fuel-pin internal pressure at end of life can be found.

$$P = \overline{P}\sigma = 0.4286 \times 4.22\times10^5$$

$$P = 181\ 000 \text{ g/cm}^2 \text{ (2570 psi)}$$

The burnup of this pin can be expressed in megawatt days per metric ton of uranium as $8.35 \times 10^4 \times B$ (or 121 500), which assumes that the density of uranium atoms in UO_2 is 2.436×10^{22} atoms per cubic centimeter and the density of U in UO_2 is 10.8 grams per cubic centimeter.

APPENDIX B

SAMPLE STAINLESS-STEEL FUEL-PIN CALCULATIONS

For a stainless-steel fuel pin, the fuel-pin diameter, the fission density in total fissions per total pin volume, the burnup fraction, the heat flux, and the internal pressure at the end of life were calculated for the following operating conditions:

Lifetime, L, sec (10 000 hr)	3.6×10^7
Inside-fuel-surface temperature, T, K	2500
Tube-wall temperature, T_s, K	1000
Gas release, A, atoms/fission	0.25
Fuel-thickness to tube-wall-thickness ratio, t_f/t	0.30
Tube-wall thickness to diameter ratio, t/d	0.15
Allowable tube-wall hoop stress, σ, g/cm^2	5.07×10^5
Enrichment, e	0.93

The values for G, $\overline{B'}$, $\overline{B}$, $\overline{Q}$, and $\overline{P}$ are found from figures 3 to 7 for the assigned values of t_f/t and t/d.

$$G = \frac{LAT(T - T_s)k_u}{d^2\sigma} = 292$$

$$\overline{B'} = \frac{B'AT}{\sigma} = 11.32\times10^{17}$$

$$\overline{B} = \frac{BATn_u e}{\sigma} = 9.57\times10^{18}$$

$$\overline{Q} = \frac{Q''LAT}{d\sigma} = 9.04\times10^3$$

$$\overline{P} = P/\sigma = 0.4286$$

From the value of $\overline{B}$, its definition, and the assigned value of pin hoop stress σ, B can be found as follows:

$$B = \frac{\overline{B}\sigma}{ATn_u e}$$

$$B = \frac{9.57\times10^{18} \times 5.07\times10^{5}}{0.25 \times 2500 \times 2.436\times10^{22} \times 0.93}$$

$$B = 0.343$$

From this value of σ, G and its definition, and the assigned variables, the pin diameter can be found.

$$d^2 = \frac{LAT(T - T_s)k_u}{G\sigma} = \frac{3.6\times10^{7} \times 0.25 \times 2500\ (2500 - 1000) \times 2\times10^{-5}}{292 \times 5.07\times10^{5}}$$

$$d^2 = 4.56$$

$$d = 2.14\ \text{cm}$$

From the expression for $\overline{Q}$, d, σ, and the assigned variables, the heat flux can be found.

$$Q'' = \frac{\overline{Q}d\sigma}{LAT} = \frac{9.04\times10^{3} \times 2.14 \times 5.07\times10^{5}}{3.6\times10^{7} \times 0.25 \times 2500}$$

$$Q'' = 0.44\ \text{kW/cm}^2$$

The internal pressure is

$$P = \overline{P}\sigma = 0.4284 \times 5.07\times10^{5} = 2.17\times10^{5}\ \text{g/cm}^2\ (3090\ \text{psi})$$

The fission per total pin volume is

$$B' = \overline{B}'\sigma = \frac{11.32\times10^{17} \times 5.07\times10^{5}}{0.25 \times 2500} = 9.22\times10^{20}\ \text{fissions/cm}^3$$

The burnup expressed in megawatt days per metric ton of uranium is $8.35\times10^{4} \times B$ (or 286 000).

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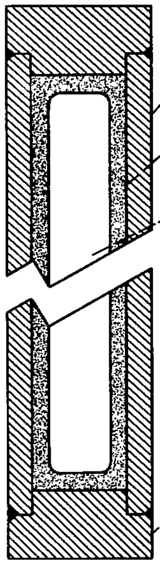

Figure 1. - Schematic drawing of very-high-burnup vapor-transport fuel-pin concept.

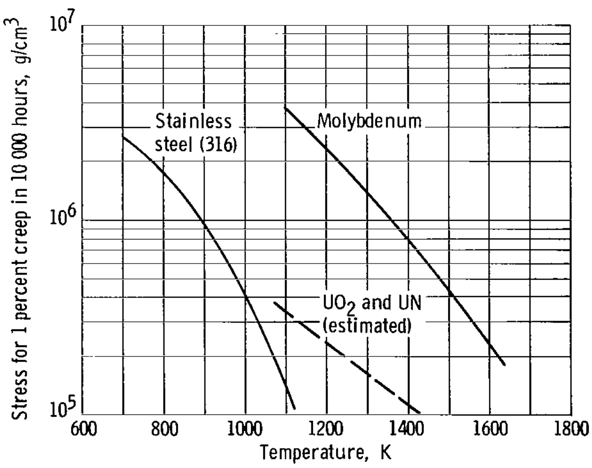

Figure 2. - Allowable creep stress for typical fuel-pin and fuel materials.

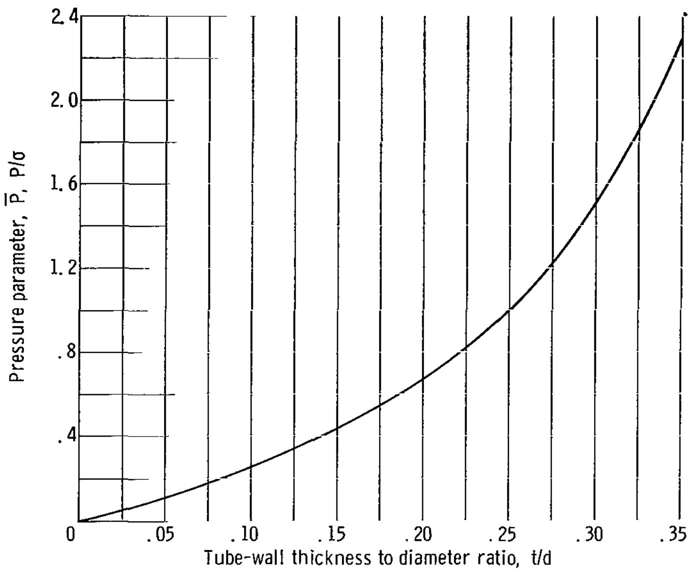

Figure 3. - Generalized pressure parameter for all fuel- to tube-wall-thickness ratios.

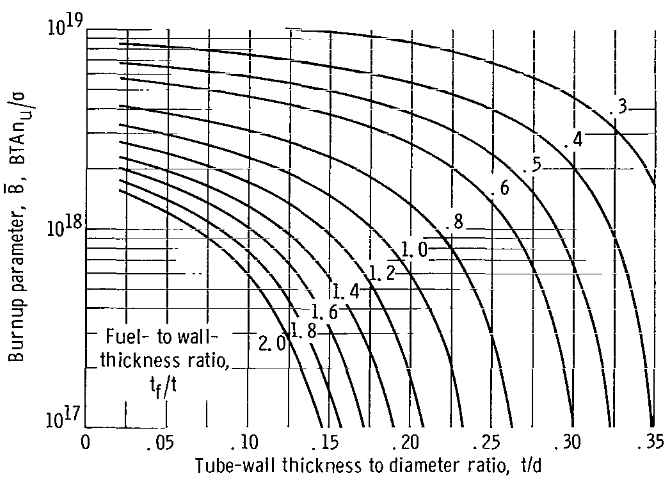

Figure 4. - Generalized burnup parameter.

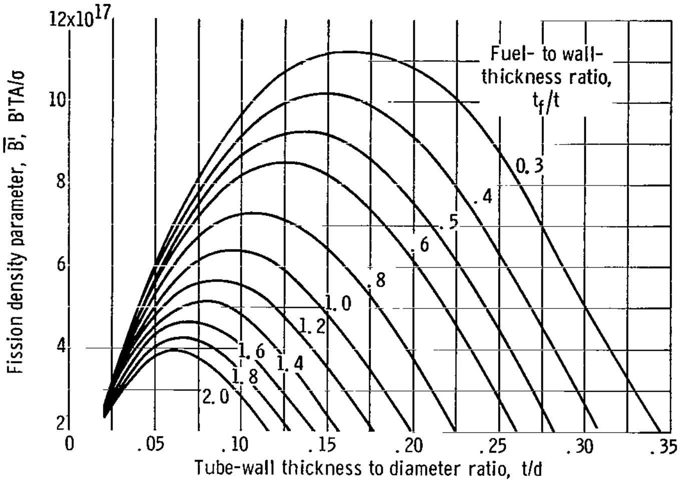

Figure 5. - Generalized fission density parameter.

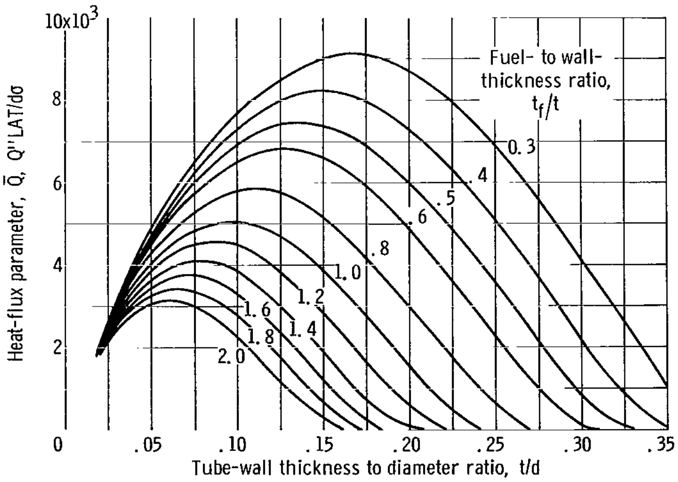

Figure 6. - Generalized heat-flux parameter.

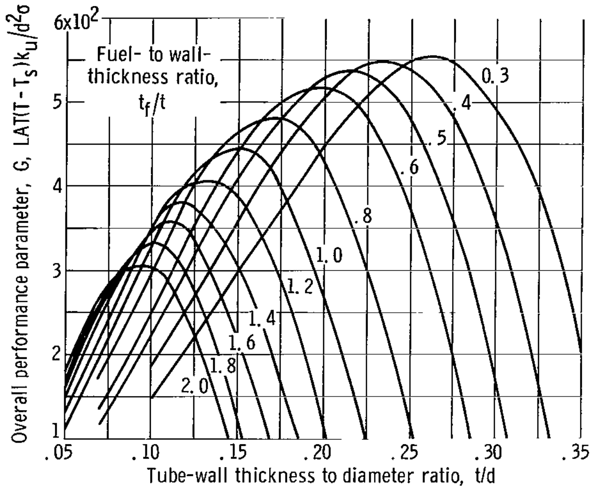

Figure 7. - Generalized overall performance parameter.

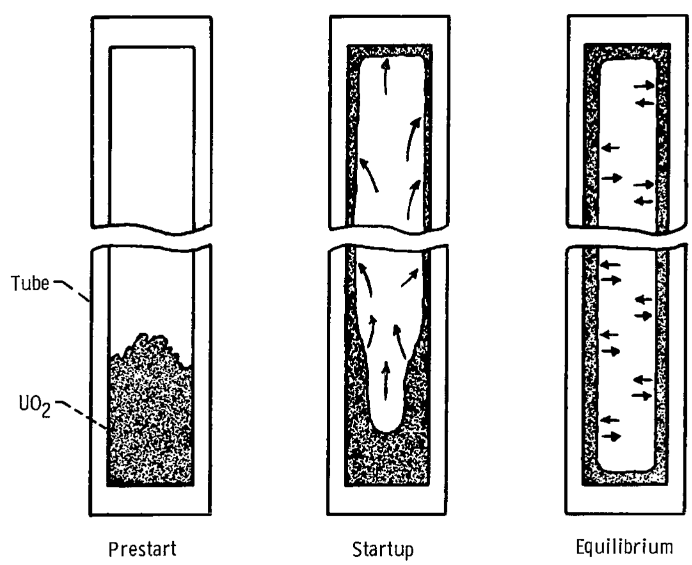

Figure 8. - Automatic fuel redistribution with very-high-burnup, vapor-transport fuel pin.

NASA-Langley, 1968 —— 22 E-4387